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Jesse W. M. DuMond

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HIGHER PRECISION IN NUCLEAR SPECTROSCOPY

By ***Jesse W. M. DuMond***

FOR NEARLY SIX YEARS there has been in existence at the California Institute of Technology a program of research work directed at increasing the precision of all measurements in nuclear spectroscopy and especially the precision with which nuclear energy levels may be determined. This trend toward higher precision of measurement is to be observed at present in nearly every area of nuclear physics (except possibly in the still new very high energy field) for it is generally realized that, while much primary qualitative information has been acquired, a real understanding and interpretation of the problems of nuclear structure and the internal mechanics of nuclei must wait for a sufficient fund of accurate and reliable quantitative numerical data to furnish a foundation for theory to build upon.

History shows that the development of knowledge in the field of atomic structure followed as a direct consequence of the development of techniques leading to precision measurements in the spectroscopy of molecular and atomic energy levels (from the infrared through x-rays). A recital of the names of Rowland, Ritz, Rydberg, Michelson, Balmer, Frank and Hertz, Laue, Bragg, Moseley, Siegbahn, Sommerfeld (the list could be extended much further, of course) is all that is needed to remind the informed student of the truth of the foregoing statement. No one conversant with history can deny that the search for the next decimal place can lead to extremely significant and important contributions to fundamental knowledge. Frequently the impetus toward higher precision comes through the specialized taste or temperament of certain scientific workers whose endowments happen to fit them for this type of work or it may be that a new technique is discovered with new possibilities as to increased precision which attracts workers to exploit it. These are fortunate accidents. The ultimate motivation however in improving the precision of physical measurements should be, and undoubtedly is, because precision almost invariably pays off directly or indirectly in the long run in the form of extremely valuable new information. Furthermore, increased precision once achieved at one point in a given field has a way of spreading out and affecting other fields in an astonishingly beneficial way which comes about because of the remarkable and intricate interrelatedness of different areas of physical knowledge.

A. C. G. Mitchell [1] has pointed out in a recent review of the spectroscopy of artificially radioactive nuclei that the accuracy in energy level determinations in this field by conventional nuclear spectroscopic methods is only 0.5 to 2% and that the resolution is usually so low that quantum energies must differ by 5% to be separated. This compares very unfavorably with the spectroscopic accuracies and resolving powers attained in the infrared, optical, ultraviolet, or x-ray regions.

One of the few laboratories in the world where serious attention has been given this problem is at the Nobel Institute in Stockholm where, under the leadership of Kai Siegbahn, a notable group of workers (A. Hedgran, N. Svartholm, G. Lindström, H. Slätis, and others) have made serious efforts by the development of special instrumentation (chiefly for the study of beta particle spectroscopy) toward increased precision of measurement both absolute and relative. A. Hedgran in a recent publication [2] lists four reasons for this interest in improving the precision of measurement which with a few additions by the present author may be paraphrased briefly as follows.

(a) From analogy with the history of atomic spectroscopy (e.g., the Balmer formula), it is hoped that increased precision will yield new information on the structure of nuclei through the discovery of numerical relationships between energy level values. S. Devons [3] has pointed out in a recently published book a few observations possibly indicative of such relationships. The Goldhabers (Gertrude and Maurice) also have much unpublished data suggesting interesting regularities of this sort.

(b) Accurate gamma-ray energy-determinations help notably to narrow down the number of possible decay schemes which can be proposed for the excited levels of a gamma-ray emitter by the application of the Ritz

Jesse W. M. DuMond is professor of physics at the California Institute of Technology in Pasadena. The present article is based on an invited paper presented last May before the American Physical Society in Washington. The work described was supported jointly by the Office of Naval Research and the Atomic Energy Commission.

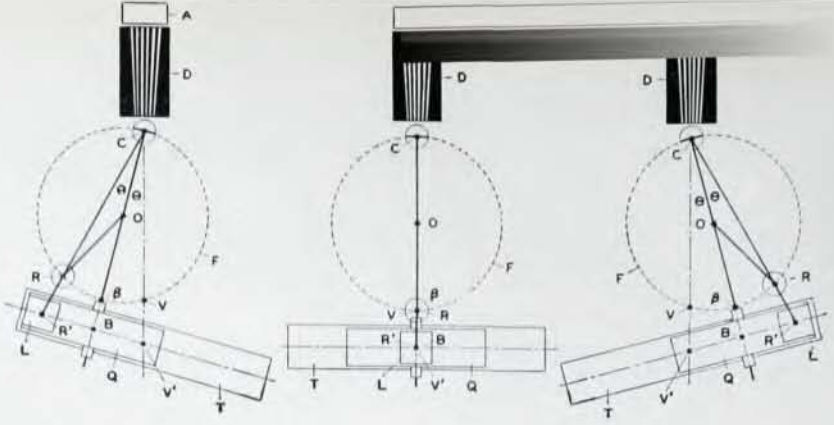


Fig. 1. Schematic illustration of the kinematics of the 2-meter focusing curved crystal gamma-ray spectrometer.

combination principle. Supposed "cross over" transitions in which the sum of two gamma-ray energies should add up accurately to equality with a third may thus prove to be false when examined with higher precision and other more complex proposed relationships of the same kind may frequently be put to the acid test in the same way.

(c) By increasing the resolution, new lines might be revealed and natural line broadening—caused, for example, by the Doppler effect—may be detected and studied.

(d) Some fundamental constants, as for example the binding energy of the deuteron [4] or the wavelength of the annihilation radiation,[5] can be determined with better accuracy if high absolute precision in nuclear spectroscopy is achieved; accurate knowledge of these constants frequently may decide questions of very crucial fundamental importance, such as the equality or inequality of the masses of positive and negative electrons.

At the California Institute of Technology, the catalyzing influence which started the program in precision nuclear spectroscopy was the successful development of the 2-meter curved crystal gamma-ray spectrometer.[6] This instrument, which in some respects resembles the transmission type curved crystal x-ray spectrometer of Y. Cauchois,[7] was designed to measure with precision far shorter wavelengths at far higher quantum energies than any previous instrument of its kind by applying precisely the same fundamental principles of crystalline diffraction to resolve into a spectrum the short wavelength gamma radiation that had been used for longer wavelengths ever since the discoveries of Laue and Bragg. The CIT 2-meter gamma-ray spectrometer has measured wavelengths as short as 9 x.u. (Co^{60} radiation corresponding to 1.3 Mev quantum energy) with considerable precision (about one part in 10^3), and this is certainly not yet the limit of the instrument.

It is the differences in the design of the CIT 2-meter instrument from the earlier transmission type x-ray spectrometers, such as that of Cauchois, which explain its ability to work with high precision at so much shorter wavelengths. These differences are best appreciated by the following description.

Fig. 1 illustrates the geometry and kinematics of the present 2-meter gamma-ray spectrometer. A curved crystal lamina of quartz held in a precision profiled clamp and mounted on a pivot at C is elastically bent so that its (310) atomic planes are made to converge in such a way that they would, if produced, intersect in a common point, β, about two meters distant from the crystal. A circle with center at O tangent to the neutral axis of the bent quartz slab at its center and passing through the point β is the focal circle of the instrument. The source of gamma-rays concentrated in a small volume at R and carried inside a lead bomb is maintained on the focal circle by a radius bar OR and made to explore that circle on both sides of the point β. In so doing, gamma-rays emanating from the source strike the crystal planes at very closely the same Bragg angle θ for all points of the crystal lamina and when this angle θ satisfies the Bragg relationship $n\lambda = 2d \sin\theta$ for some gamma-ray wavelength λ emitted by the source there will occur a strong reflection from the crystal planes which will be recorded by an increased counting rate of the NaI(Th) scintillation crystal counter at A. The selectively reflected monochromatic radiation leaves the crystal at C in a diverging beam whose virtual source is a point V also on the focal circle such that the arcs $V\beta$ and βR are equal. The heterogeneous beam from the source R, directly transmitted through the crystal at C, may easily be 2000 times as intense as the selectively reflected monochromatic beam which it is the function of the scintillation detector at A to measure and therefore a carefully made "collimator" D consisting of tapering slots separated by tapering die-cast lead partitions (all of whose surfaces converge toward the point V) is provided to suppress this direct beam and accept only the selectively reflected beam. The collimator has nothing to do with the spectral resolving power of the instrument and serves only the purpose of a baffle which, for all wavelengths greater than a certain minimum, rejects the directly transmitted beam and accepts the selectively reflected beam. The present collimator, whose angular resolving power is about fifty times coarser than the quartz crystal, will permit working up to energies of about 1.5 Mev (or down to wavelengths of about 8 milliangstroms) before scattering and leakage of the direct beam on and through its walls precludes further work in the first order of reflection. It was because of the weight of this heavy collimator, and of the heavy lead shielding (not shown in Fig. 1) surrounding the detector at A, that the present design was made with both focal circle and source movable so that in a spectral exploration the outgoing selectively reflected beam would be the stationary feature. To accomplish with requisite precision this motion of rotation of the focal circle around the crystal pivot C and simultaneously also the exploratory motion of the source at R along the focal circle, a long track T pivoted at V and two carriages, Q running on

Fig. 2. General view of 2-meter curved crystal gamma-ray spectrometer.

track T, and L running on Q, are provided. The carriage Q contains two long precision lapped screws standing one directly above the other and geared together with equal gears. The upper screw drives the carriage L relative to Q by means of a nut at R' while the lower screw drives the carriage Q relative to the pivoted track T by means of a nut at V'. A lower beam $CO\ \beta$ is pivoted at C and is provided at its extremity with a 1¼-inch round bar which slides smoothly through ball bearing guides passing transversely through the carriage Q. This is intended to insure at all times perpendicularity of the beam axis COB and the plane $V'BR'$ lying in the axes of the two screws. This lower beam is rigidly attached through an axle to the table carrying the crystal at C so that the crystal, the lower beam, and the focal circle defined by the pivot at O and radius bar OR, all move together as one rigid reference system. An upper beam CRR' pivots freely at C on the axle supporting the crystal table so that it can turn at twice the angular rate of rotation of the former. The outer end of this upper beam is supported on a pivot at R' on the small carriage L. The source at R in its lead shielding bomb is supported on a carriage running longitudinally on ball bearing ways on the upper beam to accommodate the change in the length CR as the radius bar OR constrains the source to remain on the focal circle during the exploration of the spectrum. CV' and CR' are exactly equal constant lengths and it should therefore be clear that displacements of carriage L away from the center B of carriage Q by means of the precision screw measure the sine of the Bragg angle θ and are therefore strictly proportional to the wavelength λ selected by the crystal. In practice, two spectral profiles of each line are always explored for reflection of the radiation from *either* side of the atomic planes of the crystal, and the complete travel of the screw in driving from one such spectral position (as shown at the left of Fig. 1) to the other (as shown at the right of Fig. 1) is used to measure the wavelength. Since the instrument is calibrated with a known and carefully measured x-ray wavelength ($WK\alpha_1$) all that is really essential is to be assured of the *linearity* of its wavelength scale, especially in the region of greatest interest for wavelengths shorter than $WK\alpha_1$. Fig. 2 shows a general view of the spectrometer, in which can be seen the curved crystal and the lower beam terminated in the 1¼-inch bar which slides transversely through the screw carriage, the swinging track on which the screw carriage runs, the upper beam which turns independently of the crystal and carries the source in a lead bomb on a rolling carriage. One can also see the radius bar which maintains the source on the focal circle.

The chief differences which distinguish this gamma-ray instrument from earlier focusing curved crystal x-ray spectrometers and account for its success in the much shorter wavelength field may now be enumerated separately in the five following paragraphs.

1. The gamma-emitting source is placed in very concentrated form at the real focus of the crystal on the focal circle of the instrument, and the radiation travelling in reverse direction to the usual one passes after selective diffraction on the internal planes of the curved crystal into the collimator and thence to a scintillation crystal detector where the selectively diffracted beam is almost completely absorbed and its intensity measured by counting the scintillations with photomultiplier tubes. Thus, instead of simultaneously recording on a curved photographic emulsion a considerable band of spectral lines as in the Cauchois or other curved crystal x-ray instruments, the spectrum is explored at successive point-by-point settings of the source on the focal circle. At each setting the instrument is arrested for a finite counting time interval while counts are accumulated by the scintillation crystal detector. The instrument settings are made automatically according to a program prearranged by punching holes appropriately in a tape, and the scaled-down counts from the scintillation crystal are recorded on a special printing mechanism which also prints the time in minutes since the spectral run was started and the setting of the spectrometer wavelength screw. A great gain in sensitivity is thus achieved over the photographic method since the scintillation crystal can be made thick enough to absorb a large fraction of the hard radiation incident upon it. Also, much more efficient use is made of a given total amount of radioactive material by concentrating it at the real focus of the instrument, since each atom of the radioactive material can radiate into the very large solid angle defined by the aperture of the curved quartz crystal. In the photographic instruments, the source, placed on the convex side of the curved crystal at some distance therefrom, must be spread over an extended area if the entire crystal window is to be used; but, for some specified wavelength, each radioactive atom in the source can only make use of a very small area of the crystal aperture where the rays from that atom strike the lattice planes at the Bragg angle. The delineation of the gamma-ray line profiles is quantitatively direct and does not involve the uncertainties and fluctuations coming from film grain, erratic variations from sensitiv-

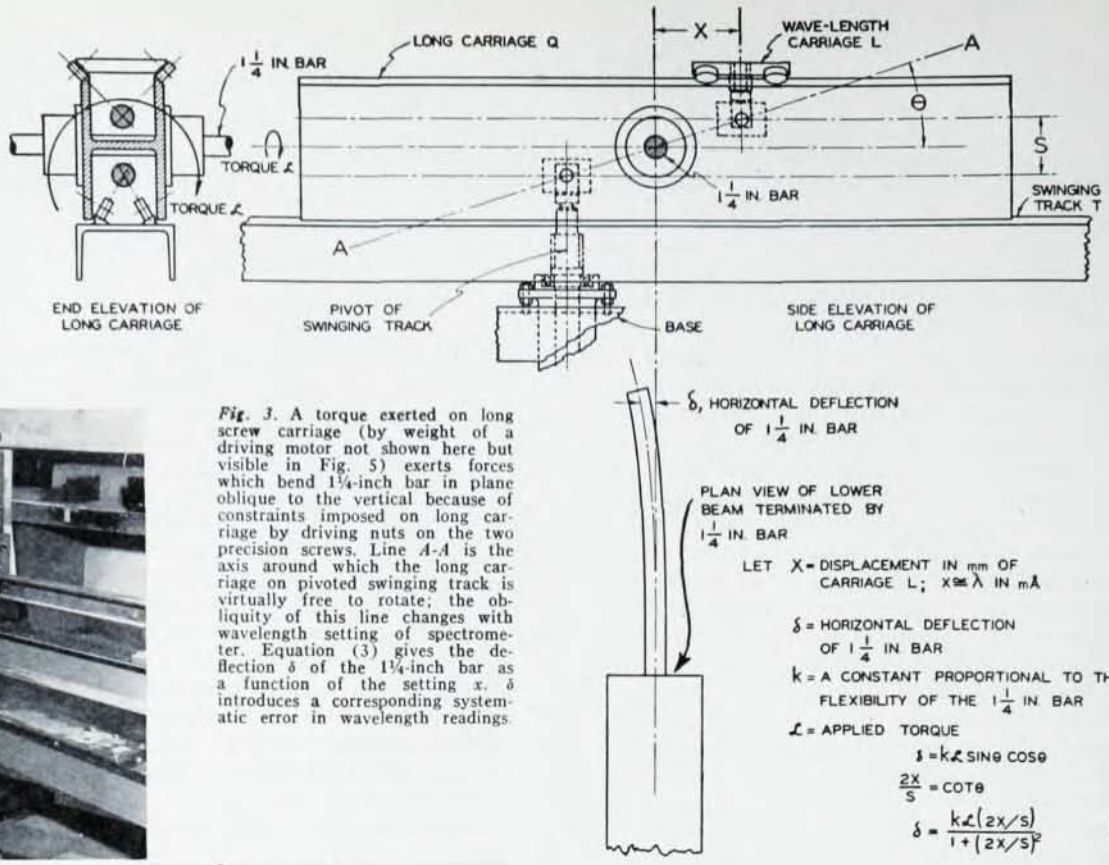


Fig. 3. A torque exerted on long screw carriage (by weight of a driving motor not shown here but visible in Fig. 5) exerts forces which bend 1¼-inch bar in plane oblique to the vertical because of constraints imposed on long carriage by driving nuts on the two precision screws. Line *A-A* is the axis around which the long carriage on pivoted swinging track is virtually free to rotate; the obliquity of this line changes with wavelength setting of spectrometer. Equation (3) gives the deflection δ of the 1¼-inch bar as a function of the setting x. δ introduces a corresponding systematic error in wavelength readings.

Fig. 4. The 6-inch concave mirror mounted above the curved crystal and rigidly related thereto so that the two turn in unison.

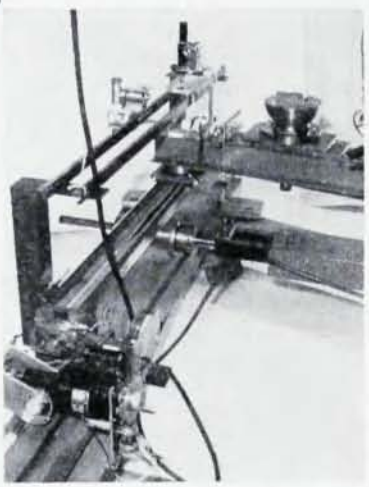


Fig. 5. The angle-iron frame mounted on long screw carriage and the two microscopes provided for precision investigation of the minute errors in the kinematics of the two-meter curved crystal spectrometer.

ity of emulsions, development technique, and subsequent measurement with a microphotometer or densitometer.

2. A technique has been developed for profiling the convex surface of the crystal clamping block to a right circular cylindrical form of radius 2 meters. This is done with such high accuracy that when an optically flat plate of monocrystalline quartz 2 mm thick and 7 × 8 cms in size is clamped in intimate contact therewith, a given gamma or x-ray wavelength (selectively reflected from the atomic lattice planes of the quartz) can be made to focus at two meters distance to within 0.05 mm of the same point for all parts of the crystal over a window area of dimensions 4 × 5 cms. This very sharp definition of focus is necessary in precision measurements of very short wavelengths.

3. The use of the diverging collimator together with the kinematics of the remainder of the instrument prevents any reflections being studied other than those from one selected set of atomic lattice planes in the quartz crystal, in the present instrument the $(31\bar{4}0)$ planes. Thus the interpretation of the spectra is considerably simplified.

4. Each wavelength measurement on a single line consists in a point-by-point delineation of two line profiles, one for reflection from each side of the $(31\bar{4}0)$ planes. The total displacement of the wavelength screw requisite to displace one of these profiles into exact match with the other is taken as the measure of wavelength. It has been shown that the wavelength uncertainty with which such a match can be made with ordinarily good statistics of counting is of order much less than 1 microangstrom and very much smaller than mechanical sources of systematic error at present existing in the instrument because of lubricating oil films and minute elastic flexures of parts.

5. Every effort has been made, first by the special design of the instrument and latterly by the careful study of minute sources of systematic error, to ensure that the corrected wavelength scale of the instrument shall be as strictly as possible proportional to the sine of the Bragg scale. The instrument has purposely been

designed to include in its range many well known x-ray lines of much longer wavelength than the shortest gamma rays it is capable of measuring. The exact constant of proportionality (between the nominal instrument scale and true wavelengths) can be readily established by measuring with the instrument certain x-ray lines (the K spectrum of tungsten was used) whose wavelengths have been established[8] with high precision on the Siegbahn scale of x-units, and since the relationship of this scale to absolute wavelengths in angstroms is known to a few parts in 10^5 through x-ray diffraction studies in grazing incidence on ruled gratings the present instrument can be regarded as a (unique) device for bridging the gap in absolute measurements between the x-ray and gamma-ray regions and placing the scale of gamma-ray wavelengths on an absolute precision basis.

IT WILL BE RECALLED that in 1948, the 2-meter curved crystal spectrometer was used to make a direct precision measurement[9] of the annihilation radiation wavelength from the positron emitter Cu^{64}. This measurement exhibited a slight discrepancy of about 6 microangstroms (in 24,000) from the expected value, $\lambda_c = h/m_0c = (2.4266 \pm 0.0003) \times 10^{-10}$ cms computed from the at that time most probable values of these constants, determined by least-squares adjustment[10] from all precision sources of information. (These sources yielded m_0 the mass of the *negative* electron.) On the wavelength screw carriage of our 2-meter curved crystal spectrometer this discrepancy (of 6 microangstroms) represented a displacement of only 12 microns and though it was about eight times the probable error of the mean of 7 independent runs computed from their reproducibility, we were not prepared to guarantee that systematic errors in our wavelength scale of this magnitude might not be present. At the time, just because of this uncertainty, we multiplied our probable error (based on reproducibility) by four to take account of such possible systematic errors.[9] Shortly after this measurement, Dr. David E. Muller introduced a very considerable improvement in the sensitivity of the 2-meter instrument by perfecting the present sodium iodide scintillation crystal detector to take the place of the earlier multicellular Geiger-Muller counters. Thanks to the resulting great improvement in sensitivity, early in 1951, Muller was able to measure, in first, second, and third orders of reflection, four different gamma-ray lines from Ir^{192}, and in first and second orders the Ir $K\alpha_1$ x-ray line.

Table I. Apparent Wavelengths of Four Strong γ-Ray Lines and One X-Ray Line Measured in Three Different Orders With 2-Meter Curved Crystal Spectrometer. (Lines are those following decay of Ir^{192}.)

	Wavelengths in Milliangstroms		
Energy	*1st Order*	*2nd Order*	*3rd Order*
295.79 Kev	41.909	41.894	41.898
308.26 Kev	40.214	40.205	40.191
316.28 Kev	39.197	39.183	39.174
467.53 Kev	26.515	26.503	26.496
Ir $K\alpha_1$	191.025	190.993	

Table I shows the results of these measurements in which it will be noted that, in all but one case, higher order reflections indicated slightly shorter wavelengths in disagreement with lower order reflections. We concluded that a hitherto unsuspected nonlinearity in the wavelength scale of our spectrometer must exist such that, in the wavelength region below the calibration point for our screw, the wavelengths indicated by the spectrometer were a little too long. (This calibration point is at 208 milliangstroms, the wavelength of the W$K\alpha_1$ x-ray line.)

Because of this clear internal evidence of a nonlinearity in our wavelength scale, we undertook in 1951 a very careful intensive study of all possible sources of error in the instrument and an extremely careful recalibration as regards the linearity of the wavelength scale. The chief causes of the trouble we have found come from mechanical flexures in some of the parts of the instrument for which we have devised optical means of detection and correction now to be described.

The chief source of nonlinearity we have found to come from minute mechanical flexures in the 1¼-inch bar, the extension of the lower beam CO β passing through the ball bearing guides in the carriage Q. (See Figs. 1 and 2.) An analysis of the forces which impose a systematic bending on this bar because of the overhanging weight of the driving motor which drives the precision screw on carriage Q was made in 1951 by D. E. Muller. He showed that the torque exerted on carriage Q by this overhanging weight tends to bend the 1¼-inch bar not in a vertical plane but around on oblique axis AA shown in Fig. 3 because of the constraints placed upon carriage Q by the two driving nuts on the two precision screws. It is the horizontal component of this bending of the 1¼-inch bar which introduces a nonlinearity in the motion of the crystal. By this argument Muller was able to deduce a theoretically predicted correction curve for the nonlinearity which bears a striking resemblance to our experimentally measured nonlinearity correction. However, our measurements have shown that in addition to this effect, there are other sources of nonlinearity which cannot be neglected. These result from (1) the effort which must be exerted by the 1¼-inch bar to swing the track T against the frictional resistance in the ball bearings supporting the track, which depends to some extent on the past history of setting, and (2) certain flexures in the base of the machine which tilt the crystal pivot to varying degrees as the weight of the wavelength carriage is shifted along the track. The optical means we have provided for studying and correcting the above mentioned faults are shown in Figs. 4 and 5.

In Fig. 4 one sees, permanently and rigidly mounted above the curved crystal, so that it turns in unison with the latter, a well-corrected 6-inch concave mirror of radius of curvature about 2½ meters. In Fig. 5 one sees the long screw carriage to which has been added a light angle-iron frame at the same level as that of the radioactive source. In the center of this frame is an

elbow microscope with its objective pointed toward the concave mirror on the crystal pivot and just above the objective is a tiny light source provided with very fine cross hairs. The image of these cross hairs, reflected by the concave mirror on the crystal pivot, is examined with the microscope and any failure of the crystal to follow the screw carriage faithfully because of flexure in the 1¼-inch bar can be detected and measured to about one micron. It is our present practice each time we make settings in profiling a given line (first for reflection from one side of the crystal planes then for reflection from the other side), to observe with this mirror and elbow microscope exactly how much shifting of the cross hairs occurs in going from one of these gamma-ray reflections to the other. We call this for brevity the "mirror correction". We have found this procedure to be distinctly superior to the use of a permanently prepared calibration curve of the mirror correction because our studies have clearly shown that this correction involves a rather large nonreproducible component, part of which is random and part dependent on the past history of wavelength settings which have been made.

With a carefully calibrated Bureau of Standards glass scale mounted on the frame above the screw carriage, clearly visible in Fig. 5, we have also calibrated the departures from linearity in the travel of the source, measured in turns of the screw, by means of the second microscope which is mounted on the upper source-supporting beam. These errors are not only due to periodic and secular errors in the screw but also to minute departures from rectilinearity in the upper ways on which the small carriage L rolls. These impart a rocking motion to that carriage which in turn is transmitted to the source through torsional flexure of the upper source-supporting beam. It is for this reason that the microscope used in this calibration is rigidly attached to the source-supporting beam with its focal plane at the same height as the radioactive source so that microscope and source will partake of identical errors of this type.

Calibration curves not shown here have been prepared by very lengthy and tedious repeated observations which extended over several months giving the secular and periodic screw corrections.

Fig. 6 shows the average curve for the reproducible component of the mirror correction. As I have already indicated, we prefer to make this correction directly with the mirror and microscope each time a measurement is being made but we have also prepared this curve to give an idea of the magnitude of the correction and also for use on old data of which we have amassed a considerable quantity. Such corrected old data is less reliable than new data in which the mirror correction is observed directly each time and we therefor plan, as part of our program, to repeat all measurements made prior to our discovery of the need for the mirror correction. The general shape of this mirror correction curve bears a remarkable general resemblance to the predictions of Muller's theory (see Eq. 3 in Fig. 3) though other factors distort its shape somewhat.

Our first measurements with these new improvements in precision were on the 0.41 Mev line of Au^{198} and on λ_A, the annihilation radiation from Cu^{64}, a very strong sample of which was prepared for us at the Argonne Laboratory and transported to us by special Navy plane at top speed so that it had a strength of 7.5 curies upon arrival in Pasadena.

Table II. Recent Results of Measurements by H. Hoyt and D. E. Muller on 2-Meter γ-Ray Spectrometer.

Wavelengths of Au^{198}, 0.41 Mev γ-line in milliangstrom units as obtained in 1st, 2nd, and 3rd orders after all corrections:

1st order	30.102 ± 0.003 mÅ	Average of 10 runs
2nd order	30.105 ± 0.002 mÅ	1 run
3rd order	30.107 ± 0.002 mÅ	Average of 2 runs
Weighted Mean	30.104 ± 0.003 mÅ	

Using DuMond and Cohen's conversion factor—December 1950, NRC Report:

$$\text{Kev} = \frac{12396.44 \pm 0.17}{\lambda \text{ (milliangstroms)}}$$

The mean value of the quantum energy of Au^{198} γ-ray line is:
411.77 ± 0.03 Kev

Table II shows the results of the Au^{198} measurements with a 5 curie source from the Argonne Laboratory. The strength was ample to permit measurements in the first three orders of reflection and it will be noted that after making all the corrections just discussed, the three different orders agree satisfactorily in giving one and the same wavelength. We believe both our wavelength and our energy values for this line to be correct now to 1 part in 10^4.

Table III. Measurements by Harry C. Hoyt on Annihilation Radiation With 2-Meter Gamma-Ray Spectrometer March 27–29, 1952. (Uncertainties given after each ± are probable errors.)

Wavelength:	
1. $\lambda_A = 24.262 \pm 0.0021$ mÅ	Cu^{64} direct measurement λ_A (Weighted mean of nine independent runs after all corrections)
2. $\lambda_A = 24.263 \pm 0.0023$ mÅ	From Au^{198} expt. + Hedgran & Lind*
3. $\lambda_c = 24.26067 \pm 0.00033$ mÅ	DuMond & Cohen—1950 L.S. analysis**
Energy:	
1. $E_A = 510.941 \pm 0.045$ kev	Cu^{64} direct measurement λ_A
2. $E_A = 510.921 \pm 0.047$ kev	Au^{198} expt. + Hedgran & Lind*
3. $m_0c^2 = 510.969 \pm 0.010$ kev	DuMond & Cohen—1950 L.S. analysis**

* A. Hedgran and D. A. Lind, Phys. Rev. **82**, 126 (1951).
** J. W. M. DuMond and E. R. Cohen, Report to National Research Council, December 1950; Phys. Rev. **82**, 555 (1951).

In Table III we show as the first item the weighted mean result of nine independent measurements (in the first order only) on the annihilation radiation wavelength from Cu^{64} after making all corrections. A special set of solid uranium slit jaws, precision finished for us

at Brookhaven by courtesy of the Atomic Energy Commission, were used to give sharp definition to the line. (The reasons why the line must be defined by means of slit jaws in the case of the annihilation radiation from Cu^{64} are explained in reference 9.) For comparison with the directly measured value, there is also shown the value computed using our measurement of Au^{198} combined with a very precise measurement by Hedgran and Lind in Stockholm[11] of the difference in $H\rho$ between converted β rays ejected on the one hand by the 0.41 Mev line of Au^{198} and on the other hand by the annihilation radiation from Cu^{64}. In Lind and Hedgran's measurement, errors in the double focusing magnetic spectrometer they used played a negligible role because the x-ray energy levels from which the β rays were ejected were so chosen that the two $H\rho$'s differed very little indeed. Finally, in this table is also shown the value of $\lambda_c = h/m_0c$, the Compton wavelength as obtained in the last least-squares analysis of December 1950, by DuMond and Cohen,[12] of all the most accurate recent data on the atomic constants. These last mentioned data are of course obtained by entirely independent methods which considerably exceed in accuracy the present wavelength measurement. It will be noted that all three of these wavelength values are now in excellent agreement. To a part in 10,000 it may now be said that we have no evidence for any difference in mass between electrons of opposite sign.

Precision wavelength measurements with the 2-meter curved crystal spectrometer of some thirty-eight different gamma-ray lines following the decay of nine different artificial or natural radioisotopes—Co^{60}, W^{187}, Ir^{192}, Ra, RdTh, Ta^{182}, Co^{127}, Au^{198}, and the annihilation radiation from Cu^{64}—have been made to date. These data have been corrected to take account of our latest above described findings of systematic error and reduced to quantum energies in electron volts.[13] The list of gamma-ray spectra so far unstudied but within reach of this method of crystal diffraction is now very large and increasing daily thanks (1) to the increased sensitivity of the instrument (as low as 30 millicuries of gamma rays can now be comfortably studied), and (2) to the improvements in nuclear techniques permitting the preparation of stronger sources.

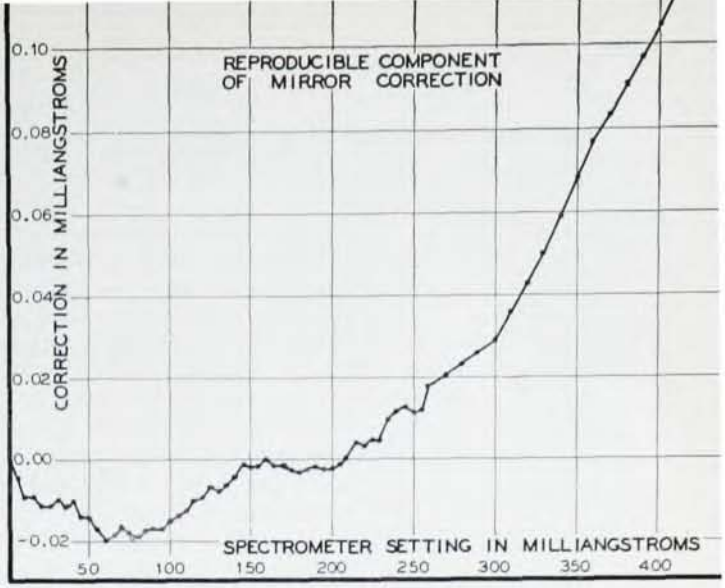
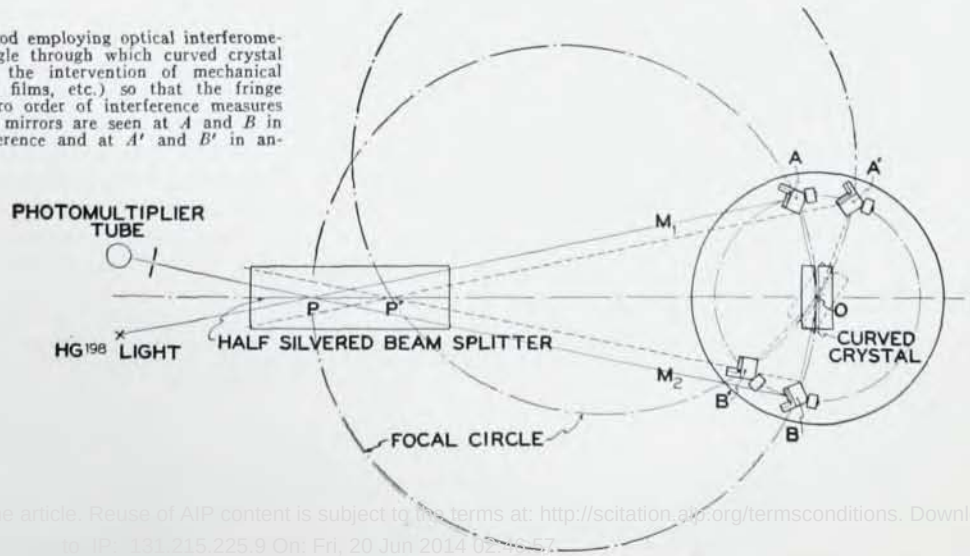


Fig. 6. Calibration curve of "mirror correction". This is the reproducible part of the correction to the wavelength scale required chiefly because slight bending of 1¼-inch bar results in a failure of the crystal to rotate in exact unison with the motion of the screw carriage *Q*.

As an outgrowth of the lessons which some of the above described experience has taught us, we now have under development and study a new instrument designed by Dr. D. E. Muller in which the sine of the Bragg angle is to be measured entirely by optical interferometry with a minimum amount of intervention of mechanism. Fig. 7 shows the principle on which this interferometer works, although the actual design is somewhat different. A beam from a monochromatic Hg^{198} light source is split by a half silvered mirror surface so that one half goes to each of two front surfaced trihedral mirrors on the pivoted disc which supports the curved crystal visible at *O*. Each trihedral mirror, when accurately adjusted, is entirely equivalent to an optical flat coinciding with the trihedral corner and appropriately oriented to return the beam incident upon it into exactly the reverse direction from whence it came. As the crystal table rotates, each of these trihedral mirrors returns the beam it receives parallel to the same initial direction as in the zero setting when the two light paths are exactly equal. The trihedral mirrors are located on the disc so that at the zero setting *PAO* and *PBO* form equal right triangles. At any other setting, it is easy to see then that the difference of the

Fig 7. Schematic illustration of method employing optical interferometry for measuring sine of Bragg angle through which curved crystal rotates. The object is to decrease the intervention of mechanical errors (lost motion in bearings, oil films, etc.) so that the fringe count away from the position of zero order of interference measures directly the required sine. Trihedral mirrors are seen at *A* and *B* in the position of zero order of interference and at *A'* and *B'* in another position.



two paths $2P'A'$ and $2P'B'$ (measured by counting fringes) is a reliable measure of the sine of the angle rotated through.

It can be readily shown that if the gamma-ray source can be made to coincide with the optical interference point P, first order errors due to shake or looseness in the pivot at O become unimportant. In the actual instrument, in order to get the beam splitting mirror out of the way of the gamma-ray source and still enjoy the benefits of freedom from errors caused by looseness or inaccuracies in pivot O, two diverting mirrors are introduced at M_1 and M_2 so that the light paths are bent out of the plane of the drawing in such a way also as to make them intersect the beam splitting mirror at a much more convenient and economical angle (from the point of view of the required size and cost of this expensive component).

It is planned to count the fringes at rather high speed with photomultiplier tubes, keeping a record of the total on a scaling circuit, and by means of a quadrature phase arrangement to cause the scaling circuits to count backward (deduct the count) when the direction of rotation of the crystal table reverses. We hope and aim at a ten-fold increase in precision over our present 2-meter instrument with this new optical interferometer, say from perhaps a part in ten thousand to a part in a hundred thousand in the half million volt region. The two trihedral mirrors and their mounts have been constructed. Each consists of three $4'' \times 4''$ flats provided with microadjustments to render the three dihedral angles accurately 90°. These components have been successfully adjusted to give circular interference fringes on a beam-splitting mirror and there is therefore every reason to expect success from the eventual instrumental design.

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[13] A table giving these results will be mailed upon request to interested physicists. A paper describing this research work with interpretations of some of the decay schemes is now in the hands of the editors of the Physical Review.

a report by th

THE Atomic Energy Act of 1946 provides in Section 2 (b) that "There shall be a General Advisory Committee to advise the Commission on scientific and technical matters relating to materials, production, and research and development, to be composed of nine members, who shall be appointed from civilian life by the President." The Act further directs that "The Committee shall designate one of its own members as Chairman. The Committee shall meet at least four times in every calendar year." Beyond that, the Act does not specify how the Committee is to perform its advisory functions, how it is to obtain the information and analysis on which to base its advice, nor how to determine the issues to which it should direct its attention.

It is now almost six years since the Atomic Energy Act became law. Three members of the General Advisory Committee will shortly have served their full statutory term. This seems to us an appropriate time to give an account of how the Committee has attempted to fulfill its obligations.

The Committee was initially appointed by the President late in 1946, and met for the first time in the early days of January, 1947. It proceeded according to the statute to elect a Chairman, as it has at the first meeting of each calendar year, and to establish a schedule for its future meetings. In the five and one-half years since its inception, it has held 30 such scheduled meetings.* These have each occupied two or three days, largely devoted to study and discussion by the Committee of documents and oral reports on the problems before it. With rare exceptions, every meeting has been attended by every member of the Committee. At the close of each meeting, the Committee has addressed, in the form of a letter from its Chairman to the Chairman of the Commission, a report of facts, and opinions, and of such advice as it was prepared to give. These

* Subcommittees and panels of the Committee have met at Los Alamos, Washington, Berkeley, Princeton, Pasadena, Oak Ridge, and the Argonne.